# INTERFERENCE OF RESONANCES AND OBSERVATION OF THE $\Theta^+$-PENTAQUARK

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After brief discussion of how the quantum interference may influence manifestations of resonances, description is given of the recent experimental evidence for possible manifestation of the $\Theta^+$-photoproduction in interference with the $\phi$-photoproduction.

## 1    General notes on quantum interference

It is widely known that Quantum physics is probabilistic. But this is not its most characteristic feature. Classical physics may also be an object of probabilistic description (such is, for example, statistical physics). The main difference is that in cases where Classical physics adds probabilities, Quantum physics adds amplitudes (or wave functions). Very important consequences are existence of interference effects and possible mixing of different wave functions (those are just the most intimate properties of Quantum physics).

As an impressive result, some particles may oscillate in time and space, transforming to each other. This quantum microscopic effect may have quite macroscopic manifestations. Characteristic oscillation distances can be as small as some mm's, or even some $\mu$m's (for neutral $B$ mesons), but can also be astronomically large (for solar neutrinos).

Hadron resonances can mix and oscillate as well, but their space-time oscillations cannot be observed, since in all realistic situations they are completely inside one atom (all resonances have $c\tau < 3 \cdot 10^{-10}$ cm; compare to $c\tau = 2.7$ cm for $K_S$ mesons). Fortunately, the mixing of resonances has visible manifestations in complementary variables, first of all, in energy (or mass in the rest frame). Here, mixing of resonances deforms their canonical Breit–Wigner peaks.

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## 2   Manifestations of resonance interferences

Typical examples of resonance interferences in various reactions are collected and discussed in the topical review [1] (see there references to the original works). This section briefly follows to that review.

### 2.1   Direct resonance interference

There exist various cases and ways where and how two (or more) resonances may interfere. The simplest (and best studied) possibility, which may be called the direct interference, appears when all decay products of one resonance can be produced also in decays of another resonance. It may appear in different reactions, but the situation most fruitful in this respect (and easiest for description) arises in the $e^+e^-$ annihilation into hadrons, with different final states. It demonstrates a great diversity of interference manifestations (for details see, *e.g.*, Ref. [1]) .

Excitation curve of a resonance without any interference corresponds to a peak which is traditionally described by the Breit–Wigner formula. In the presence of interference, familiar imagination for the excitation curve combines clear dip and bump (in this or in the opposite order), corresponding to destructive and constructive interferences. It is true indeed in some cases, *e.g.*, for the $\phi$ meson in the reaction $e^+e^- \to \pi^+\pi^-\pi^0$ (interference with the $\omega$ meson, see Fig. 2 in Ref. [1]).

However, it is not always so. Vicinity of the $\phi$ meson in the reaction $e^+e^- \to \eta\gamma$ does not show a clear-cut dip. Instead, the left and right foots of the $\phi$-peak are very different (about ten times, see Figs. 3 and 4 in Ref. [1]). This is a result of interference with $\rho^0$ and $\omega$ mesons, which makes the right foot of the $\phi$-peak lower than the left, as a part of a broad dip.

Each of two above examples explicitly demonstrates both constructive and destructive interferences. The pair of resonances $\rho^0$ and $\omega$ (probably, the most famous example of resonance interference) shows that only one kind of interference, constructive or destructive, may be visible.

Indeed, in the reaction $e^+e^- \to \pi^+\pi^-$, where contribution of the $\omega$ is very small, destructive interference "bites off" part of the $\rho^0$-peak, without any visible $\omega$-peak of constructive origin (see Figs. 5–7 in Ref. [1]). On the other side, in $e^+e^- \to \eta\gamma$, the $(\rho^0, \omega)$-peak has its vertex at the $\omega$-mass, though the contribution of $\rho^0$ is larger. This is the result of constructive interference, while destructive interference produces here only a barely visible break in the left side of the combined peak (see Figs. 3 and 4 in Ref. [1]).

Reaction $e^+e^- \to \pi^0\gamma$, where the $\rho^0$-contribution is small in comparison with $\omega$, shows another picture. Here the $\omega$-peak looks as an undistorted Breit–Wigner peak, but its tails, both left and right, are enhanced by constructive interference with the $\rho^0$-meson (see Fig. 8 in Ref. [1]). Similar is the situation in the reaction $e^+e^- \to \pi^0\pi^+\pi^-$ (Fig. 2 [1]), where the $\rho^0$-contribution is also very small, being suppressed by isospin violation.

In some cases interference can even transform a resonance peak into dip. Such are manifestations of the $\phi$ meson in the reaction $e^+e^- \to \omega\pi^0$, with subsequent different decays of the $\omega$ (see Fig. 9 [1]).

Those examples demonstrate that the direct interference can distort resonance peaks, sometimes very essentially. Effect for the same resonance may appear different in different reactions and for different decay modes. In any case, the direct interference became a good instrument to search for (and study) rare decays of known resonances.

The reason is rather evident. If an amplitude is small, its direct effect has the 2nd order smallness, while its interference has only the 1st order smallness and may be additionally enhanced by multiplying the small signal amplitude by a large background amplitude. Some rare decay modes would never be discovered and measured without interference. For example, the decay $\phi \to \omega\pi^0$ has $\mathrm{Br} \approx 5 \cdot 10^{-5}$ [2], being twice suppressed, by both the Zweig rule and isospin violation. Without interference, it would be completely buried in fluctuations of non-resonant events.

## 2.2    Rearrangement interference

Besides the direct interference, there is a possibility that only some (or even one) of final particles may come from any of two interfering resonances (it reminds the famous two-slit experiment, where a single quantum particle may pass through one or another of two slits). Such kind of interference can be called rearrangement (or rescattering) interference.

This phenomenon is known since 1960's. For example, processes $\pi^+ p \to \pi^+\Delta^+$, $\pi^+ p \to \pi^0\Delta^{++}$, $\pi^+ p \to \rho^+ p$ produce, after decays of resonances, the same final state $p\pi^+\pi^0$. Therefore, reaction $\pi^+ p \to p\pi^+\pi^0$ should (and does) reveal specific interference of the resonances $\Delta^{++}$, $\Delta^0$, $\rho^+$ with each other. Interference of such a kind may arise also in decays of baryons or mesons with three or more hadrons in the final state.

Rearrangement interference, as well as direct one, distorts the resonance peaks and spoils measurements of their masses and widths. To reject this effect, kinematical re-

gions, where the interference is most efficient, are usually cut out. That is why the rearrangement interference continues to be badly investigated and understood.

Nevertheless, it begins to be also used as an instrument for solving various physical problems. It was applied, *e.g.*, to eliminate ambiguity in $CP$ violation studies of $B$ meson decays [3] (see also discussion in Ref. [1]).

## 3    Problem of the $\Theta^+$-pentaquark

As a new step in similar direction, it was suggested to apply the rearrangement interference to search for new resonances with small production cross section [4]. Specifically, the reaction $\gamma p \to K^0 \bar{K}^0 p$ was suggested to look for the signal of the $\Theta^+$ baryon in interference with the $\phi$-photoproduction.

### 3.1    Microreview: status of the $\Theta^+$

After a number of discussions in framework of the Chiral Quark Model, there appeared the first theoretical paper [5] which suggested relatively certain properties for the strange baryon with $S = +1$, later called $\Theta^+$: the mass $\sim 1530$ MeV, decays to $pK^0$ and $nK^+$, the total width $< 15$ MeV. This baryon cannot consist of three quarks as usual, it is the exotic pentaquark $uudd\bar{s}$.

Experimentally, there appeared about ten papers with evidence for the $\Theta^+$, and about ten papers with negative results, some of them having higher statistics (for references, see, *e.g.*, Ref. [6]). As a result, both Particle Data Group's position since 2008 and the common opinion of the high energy physics community are the same: *the pentaquark baryon is dead*! Strangely, this does not prevent great enthusiasm in searches for exotic tetraquark mesons.

After 2008, some experimental collaborations withdrew their earlier positive results, but others (LEPS and DIANA in particular) confirmed observations of the $\Theta^+$ (see references in paper [6]).

Meanwhile, it was shown [7] that all the data, both positive and negative, can be reconciled, at least qualitatively, if multiquark (exotic) hadrons are mainly produced from many-parton states (higher Fock components of hadrons). Such states are always related to short-term fluctuations, and, if this hypothesis is true, production of exotic hadrons may be considered as a new kind of hard processes. Similar to all other hard processes, exotics production should have small cross section.

Experimentally, smallness of the $\Theta^+$-production (if it exists at all) was demonstrated by the CLAS analysis of the reaction $\gamma p \to K\bar{K}p$ [8]. The $\Theta^+$ was not observed, and strict bound was provided for its production cross section. This stimulated both the suggestion [4] and searches for an enhanced signal in rearrangement interference, which resulted in the paper [6].

### 3.2  Evidence for a possible $\Theta^+$-signal in interference with the $\phi$ meson

The new analysis of reaction $\gamma p \to K_S K_L p$ [6] used the same data set as the earlier analysis [8] and was, to some extent, similar to it. In both analyses one kaon was reconstructed by the peak in the mass of $\pi^+\pi^-$ pairs, the other by the peak in the missing mass $M_X(p\pi^+\pi^-)$. But the analysis [6], in difference with Ref. [8], applied some additional requirements to improve identification of the $K_S$. In both analyses the $K_S K_L$ spectrum shows a very pronounced $\phi$-peak. In Ref. [8] it was traditionally cut out, by applying the condition $M_X(p) > 1.04$ GeV. Analysis of Ref. [6], just opposite, used events under the $\phi$-peak, with $M_X(p) = 1.02 \pm 0.01$ GeV, where interference is most efficient.

The distribution in $M(pK_L)$, determined experimentally as $M_X(K_S)$, shows now a peak when applying two additional cuts, separately or together [6]. One of them restricts $M(pK_S)$ to eliminate known $\Sigma^*$'s in the interval $1.5 - 1.7$ GeV, which otherwise provide strong background in $M(pK_L)$ due to kinematical reflections. Another cut restricts momentum transfers, to separate a definite (mainly diffractive) mechanism of
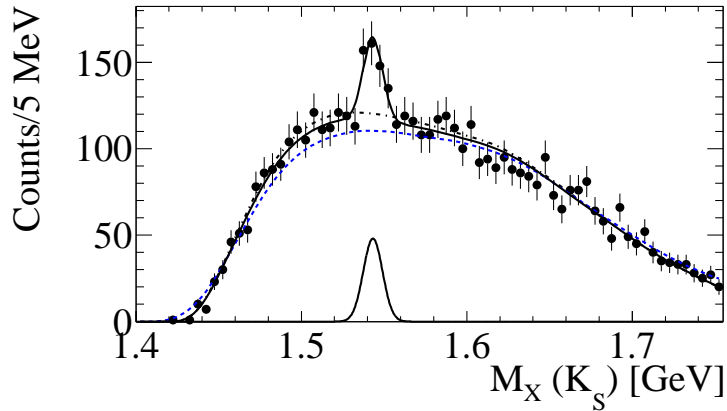


Figure 1: Distribution over $M_X(K_S) = M(pK_L)$ with cut $|t_{\gamma K_S}| < 0.45\,\text{GeV}^2$ [6]

the $\phi$-production. An example of arising spectra is shown in Fig. 1. The background is described by the Monte Carlo simulation based on the known Titov–Lee model for the forward $\phi$-photoproduction off nucleon [9]. The model is theoretically meaningful (mainly Pomeron exchange) and experimentally quite adequate. It well describes the whole spectrum of Fig. 1, except of a narrow peak near $M \sim 1.54\,\mathrm{GeV}$, its width consistent with resolution. Statistical significance of the peak is about $5.3\,\sigma$. This peak should, of course, exist in $M(pK_S)$ as well, but it is not seen in this spectrum, because of worse resolution (in agreement with the Monte Carlo simulation).

The strangeness of $pK_L$ is not fixed, it is either +1 or –1. Thus, if the peak corresponds to a new baryon state, this baryon can be either the $\Theta^+$ or a new $\Sigma^{*+}$. The latter case looks less probable because of very small width and very low intensity of production, unusual for $\Sigma^*$'s. Moreover, $\Sigma^*$ should also have hyperon decays without kaons. However, no peak in $M_X(K_S)$ near $1.54\,\mathrm{GeV}$ is seen when selecting the final state $K_S X$ without $K_L$ [6]. Both arguments prefer the $\Theta^+$, though do not prove it. To finally prove that it is just the pentaquark baryon $\Theta^+$, one needs to confirm existence of a direct photoproduction signal (without interference) and then find the peak in a system with the definite strangeness (e.g., in $nK^+$).

## 4  Conclusions

- Interference of resonances is a good instrument for solving many problems. Direct interference became familiar to search for and study rare decays of known resonances. Rearrangement interference may be useful to amplify faint signals of known or unknown resonances, with any quantum numbers (the signal could be faint because of either small branching ratio or suppressed production).

- A reliable signal has been found in rearrangement interference with the $\phi$ meson which may give evidence for possible photoproduction of the pentaquark $\Theta^+$. The final confirmation awaits for finding both a direct signal of this process and a signal with definite strangeness. But even now one can rephrase Mark Twain's letter to say: "The report of $\Theta^+$'s death was an exaggeration".

- Confirmation and investigation of multiquark hadrons may open new directions both for hadron spectroscopy and for QCD studies in general.

## Acknowledgements

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